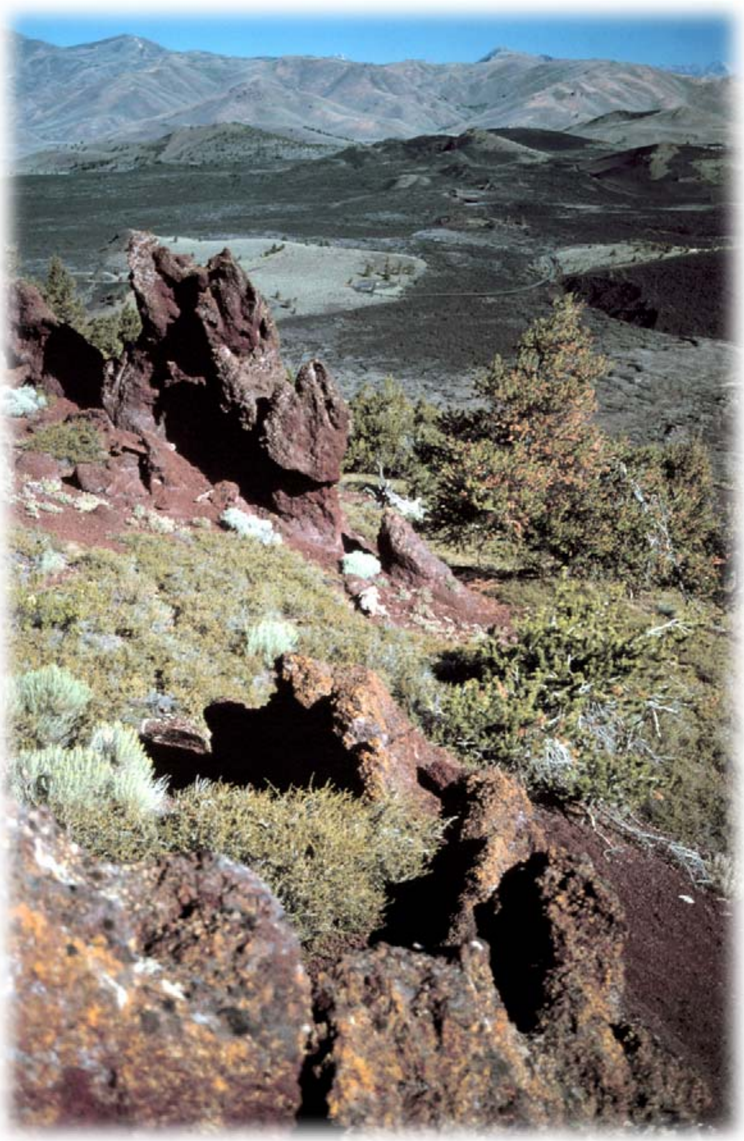
Craters of the Moon National Monument



Geologic Processes & Human Influences that Affect those Processes

Data Set Report (GPRA goal Ib4)

Scoping Meeting Held
August 31 –
September 1, 2000

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Geologic Resources Division • National Park Service • Denver, CO

Executive Summary

A scoping meeting was held at Craters of the Moon National Monument on August 31 - September 1, 2000 with the purpose of bringing together the park staff, geoscientists, and other subject matter specialists to address the issue of human influences on geologic processes at the park. Through institutional knowledge, these experts identified geologic processes active in the park and the known human activities affecting these geologic processes. This report summarizes the group's findings and satisfies a requirement of the Government Performance Results Act (GPRA) goal Ib4. Craters of the Moon National Monument was selected as the "pilot" park to test the use of scoping meetings as means of obtaining information for this performance management goal.

This report addresses the geologic processes at work in the park, the importance of those processes to the ecosystem, and the influence of humans on those processes. The scoping meeting work group identified seventeen geologic processes that occur in the park. Of these seventeen processes, eight were considered to be highly significant to the park ecosystems. Four of these highly significant processes concern the availability of water, which is scarce and critical to plants and wildlife in the park's arid environment. These processes are: geological controls on perched water systems; groundwater level; streamflow; and wetlands extent, structure and hydrology. The other significant processes are: desert microbiotic crusts and pavements; eolian processes; volcanic unrest; and cave temperature and humidity regime. Because of their significance, we suggest they be considered as candidates for monitoring or further inventory and study. At a minimum the park may want to consider gathering further information about these geologic processes.

This report also highlights geologic processes that have high management significance due to safety concerns, administrative use of resources and protection of fragile resources from detrimental human activities. Frost wedging causing rock fall in lava tubes and prospective volcanic and seismic unrest can clearly be hazardous to humans and need to be monitored in order to protect visitors and park staff. Both surface water and groundwater quality are important to managers because this water is used for park operations. Likewise, streamflow and wetland health are concerns to managers because the park's withdrawal of water may be damaging these critical resources. Cave temperature and humidity regimes are also significant to managers because cave ecosystems are very sensitive to human disturbance.

An additional objective of the scoping meeting work group was to identify geologic processes influenced by human activities. This report discusses the four primary areas where geologic processes are being influenced by human activities:

- In-stream flow of Little Cottonwood Creek altered by park administrative water withdrawals that influence the riparian ecosystem.
- Stream channel morphology (shape) changes caused by past mining activities (for which there has been some reclamation), and historic diversion of lower Little Cottonwood Creek and Leach Creek altering the natural flow paths of these streams.

- Soil and sediment erosion caused by parking lots and roadways impeding infiltration and increasing and concentrating runoff where the water leaves the pavement.
- Social trails causing soil compaction and accelerated down slope movement of material on cinder cones. Walking off trail also accelerates the break up of fragile lava crusts on lava flows exposing altered material below.

This report concludes with seven recommendations to minimize human influences on geologic processes, identifies ten inventory and monitoring needs and lists several possible research topics.

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1.0 Introduction

The National Park Service is gathering information to meet its performance management goals and provide a knowledge base to meet its stewardship responsibilities. To better understand geologic resources in parks, the NPS developed a servicewide goal to identify geologic processes at work in the parks and areas where human activities are influencing natural rates of change. A scoping meeting was held at Craters of the Moon National Monument on August 31 - September 1, 2000 with the purpose of bringing together the park staff, geoscientists, and other subject matter specialists to address this goal. This report summarizes the group's findings and satisfies a requirement of the Government Performance Results Act (GPRA) goal Ib4.

Ecosystem management is holistic and requires an understanding and integration of biological and social components, as well as, an understanding of the physical setting, including geology (Hughes and others, 1995). An area's geologic setting and physical processes affect both landforms and natural vegetation, which in turn influence the distribution of habitats. Many changes to ecosystems can be traced directly to human alteration of the physical environment including geologic processes. The following sections of this introduction provide information about the intent of the GPRA goal, geology's role in the ecosystem and the park's unique features.

1.1 GPRA Goal Background

In 1999, the Geologic Resources Division and the NPS Strategic Planning Office cooperated to develop a service-wide geologic resource goal as part of the Government Performance and Results Act (GPRA). The NPS Goal Ib4 states, "Geological processes in 53 parks [20% of 265 natural resource parks] are inventoried and human influences that affect those processes are identified". This goal is a knowledge based goal designed to improve park capabilities to make more informed science-based management decisions. It was the intention of the team that designed this goal that it be the first step in a process that would eventually lead to the mitigation or elimination of human activities that severely impact geologic processes, harm geologic features or cause critical imbalance in the ecosystem.

1.2 Park Selection

This park was selected as a participant in the geology evaluations due to its unique geologic resources and human use. Because the GPRA goal includes only 20% of the parks, information gathered at this park may also be used to represent other parks with similar resources or patterns of use, especially when findings are evaluated for service-wide implications.

Additionally, Craters of the Moon National Monument was selected because of the opportunity to combine this scoping meeting with a previously planned Vital Signs meeting scheduled for August 29 – 31, 2000. Craters of the Moon National Monument was the first park to "pilot" the concept of holding a scoping meeting as a means of obtaining information for this performance management goal.

1.3 Geology's Role in the Ecosystem

The geologic resources of a park – soils, caves, fossils, streams, springs, volcanoes, etc. – provide the precise set of physical conditions required to sustain the biological system. Interference with geologic processes and alteration of geologic features inevitably affect habitat conditions. For example, the channelization of the Virgin River in Zion National Park caused the channel to incise, lowering the groundwater table and reducing the habitat of floodplain obligate species (Steen, 1999). For a more detailed discussion of geologic processes and the role in the ecosystem see Appendix 2 and 5.

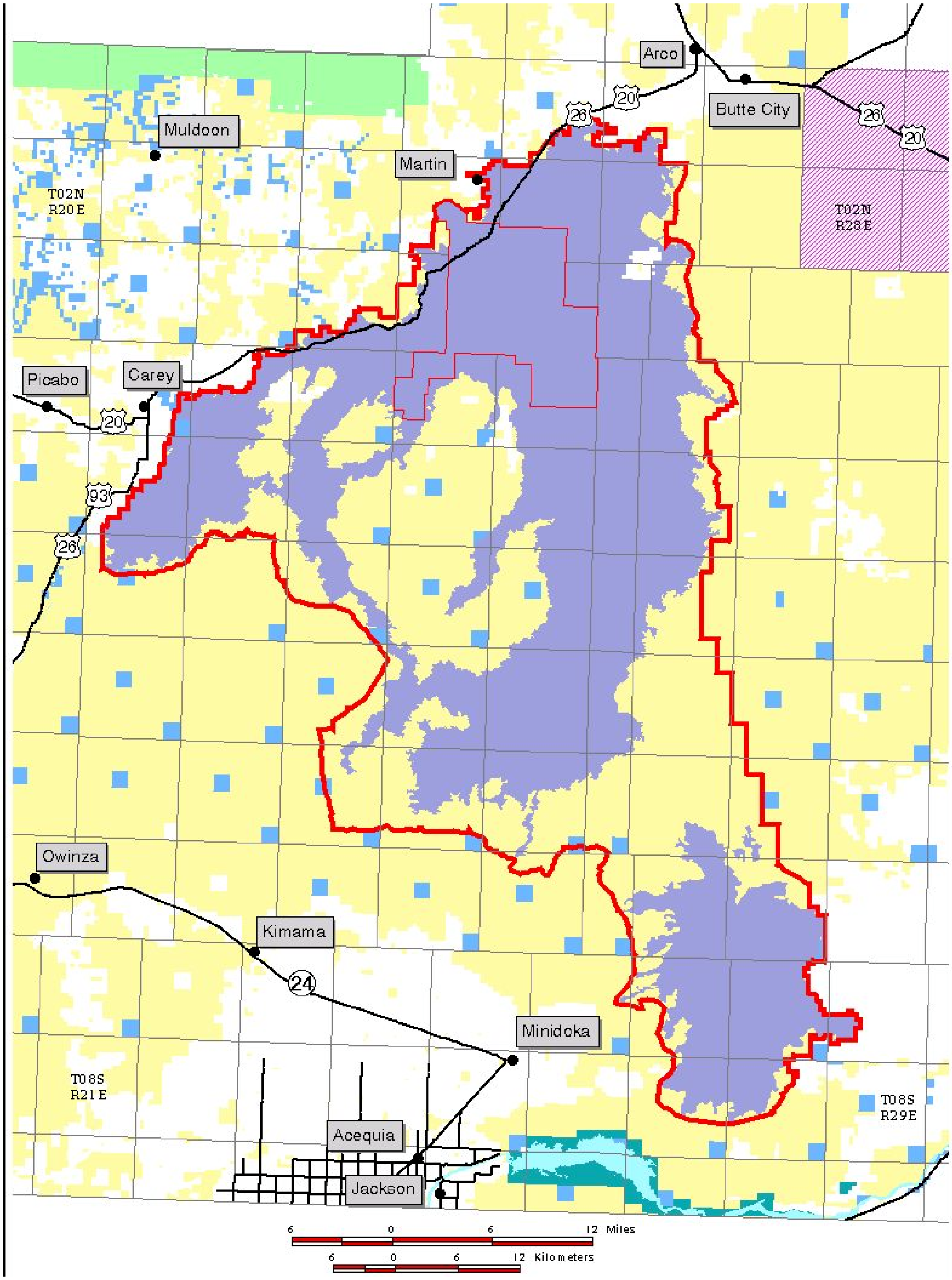
1.4 Geoindicator background

It may be difficult in any particular environment or ecosystem to separate the human influences from the geologic ones. To assist in this task, the concept of "geoindicators" has been adopted by the NPS. The basic geoindicators tool is a compiled checklist of geological indicators of rapid environmental change. The list includes 27 earth system processes and phenomena that are liable to change in magnitude, direction or rate over periods of 100 years or less (Appendix 4). They measure both catastrophic events and those that are more gradual, but evident within a human life span. To an extent, geoindicators may be as a measure of ecological health. Geoindicators are not geologic processes. However, there is a strong correlation between the two (Appendix 5). Because geoindicators represent a landscape measurement, one that concentrates on physical processes and their interactions with biologic and human components, they are uniquely suited to assess human vs. natural causes of change in the ecosystem.

1.5 Park Setting and Resources

Craters of the Moon National Monument is located on the northern edge of the Snake River Basin - High Desert (Omernick, 1986) in south central Idaho. Established in 1924, the monument encompassed 53,440 acres of federal land. On November 9, 2000 by Presidential Proclamation No. 7373 (65 CFR 69), Craters of the Moon National Monument was expanded 13 ½ times its original area to a total of 714,727 acres (see Map 1). Most of the area included in the expansion was south of the original park boundary and incorporated primarily Bureau of Land Management (BLM) lands. The monument protects a unique series of volcanic features along the entire length of the Great Rift.

Map 1. Craters of the Moon National Monument, ID (Map legend on next page).



CRATERS OF THE MOON NATIONAL MONUMENT

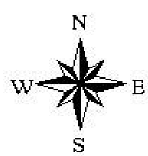
Boundary Enlargement

Land status current as of November 2000

- Cities
- Major Roads
- Craters of the Moon Expanded Boundary
- Original Craters of the Moon Boundary
- Township Lines

Land Status as of November, 2000:

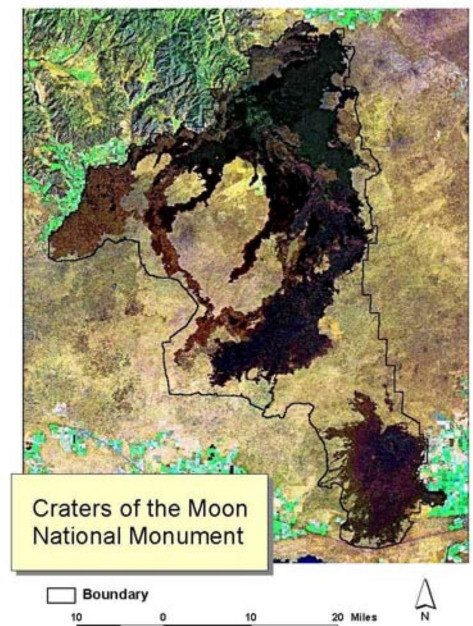
- BLM
- Private
- State
- Water Bodies
- Forest Service
- National Park Service
- National Wildlife Refuge
- Department of Energy



No warranty is made by the
Bureau of Land Management
for use of the data for purposes
not intended by the BLM.
Map date: December 15, 2000

Specific language in the original proclamation establishing the monument includes these statements concerning geologic resources (Proclamation No. 1694, May 2, 1924 – 43):

> *"Whereas, there is located....an area which contains a remarkable fissure eruption together with its associated volcanic cones, craters, rifts, lava flows, caves, natural bridges, and other phenomena characteristic of volcanic action which are of unusual scientific value and general interest; and*
>
> *Whereas, this area contains many curious and unusual phenomena of great educational value and has a weird and scenic landscape peculiar to itself...".*



The monument's north end extends into the foothills of the Pioneer Mountains. Elevations range from about 4,300 feet at the southern end of the Wapi Lava Field to about 7,700 feet in the Pioneers. With the exception of the Pioneer Mountains, monument landforms dominantly resulted from a series of volcanic basaltic eruptions which occurred over the past 15,000 years, with the most recent being about 2000 years ago.

Vegetated areas of the monument are dominated by sagebrush communities intermixed in areas with open stands of limber pine. Douglas-fir and aspen occur on the north-facing slopes of older cinder cones and in the Pioneer foothills. Deep tension fractures, lava tubes, and tube skylights create microenvironments that support plants that are not typically found in the desert, such as large ferns.

Aquatic resources are limited to two small perennial streams draining the Pioneer Mountains on the north end of the monument and year-round ice deposits in some lava tube caves and pit craters. Wildlife includes mule deer, elk, black bear, and moose; although the latter three species have generally been restricted to the Pioneer Mountains. A number of sagebrush obligate species (sage and Brewer's sparrows) are common within the monument, although sage grouse observations have been rare. Lava tube caves are used as hibernacula and for maternity colonies by a variety of bats, including the Townsend's big-eared bat.

Cultural resources are largely confined to surface or subsurface archeological sites. Only two 50+-year-old structures remain within the monument and both are located within the area of the visitor center development complex. A section of the historic Oregon Trail's Goodale's Cutoff crosses the north end of the monument.Developments within the monument are relatively limited; the visitor center complex (visitor center, maintenance shops, employee residences, and a 52 site campground), a little over 10 miles of paved roads counting the loop drive and spur roads, and potable water system. The monument is transected by State Highway 93/20/26 along the north end of the monument.

1.6 Geologic Setting

The Craters of the Moon Lava Field is a composite field made up of about 60 lava flows and 25 cones. It is the largest and most complex of the late Pleistocene and Holocene basaltic lava fields of the Eastern Snake River Plain, and is the largest lava field of its type in the lower 48 states. It has nearly every type of feature associated with basaltic systems, and park trails offer convenient access to most of them. The flows of the Craters of the Moon Lava Field have parent magma similar to that in the rest of the Snake River Plain, but exhibit a wide range of chemical compositions due to: (1) crustal contamination from assimilating older rocks, which produces lava with silica ($SiO2$) ranges of ~49% to 64%, or (2) crystal fractionation, which produces lava with silica ranges of ~44% to 54%.

The Craters of the Moon Lava Field is the northernmost of the 3 lava fields found along the Great Rift, a system of crustal fractures that begins at the base of the Pioneer Mountains north of the Monument and extends for more than 50 miles to the southeast. The Wapi Lava Field is the southernmost of these three fields. The Craters of the Moon Lava Field formed from magma that pushed up along the Great Rift. The magma that formed the Kings Bowl and Wapi Lava Fields also came up along the Great Rift, but originated in a different magma chamber. The Great Rift and other volcanic rifts on the Eastern Snake River Plain are predominantly parallel to, but not all are collinear with, basin and range faults north and south of the plain.

The Craters of the Moon Lava Field was formed during eight major eruptive periods over the past 15,000 years. In contrast, most of the other lava fields on the Eastern Snake River Plain (including Kings Bowl and Wapi) represent single eruptions. Although these eruptions were widely scattered in space and time, they share nearly identical chemical composition (producing lava with silica ranges of ~45% to 48%). The typical Eastern Snake River Plain basalts are classified as diktytaxitic olivine tholeiite lavas.

1.6.1 Geologic History

Between approximately 8 and 10 million years ago, the Yellowstone Hotspot was beneath Craters of the Moon. This time was characterized by violent rhyolite eruptions and caldera formation. Many geologists think the Yellowstone Hotspot formed just 17 to 18 million years ago; a few think it is much older. More and more evidence points to the hotspot having formed in the Earth's upper mantle at a depth of about 125 miles, rather than being a mantle plume from the core/mantle boundary. The hotspot has a plume shape, but the plume is probably not completely molten. It is a column of hot rock, which may have been produced by radioactive decay, in which some of the molten rock flows upward. The column flows upward until it hits the overlying North American Plate, which consists of the crust and the uppermost mantle, and is colder than the upward-flowing magma. Periodically, blobs of iron-rich basaltic magma rise up into the crust from a depth of about 50 miles. In the crust, these molten blobs melt overlying silica-rich rocks and form sponge-like magma chambers of partially molten rhyolite.

Catastrophic eruptions of huge volumes of rhyolitic magma have taken place along the Eastern Snake River Plain about 100 times in the past 16.5 million years. These eruptions often produced huge craters called calderas; some are 10 to 40 miles wide. Many of the approximately 100 calderas overlapped and may be associated with 7 to 13 volcanic centers. Although some of the mountain ranges that existed on the Eastern Snake River Plain before the hotspot may have been blown away by the eruptions, it is more likely that they were swallowed up as the floor of the caldera sank during the violent explosions.

The Yellowstone hotspot itself is stationary. Rather, it is the North American Plate that has been moving in a southwesterly direction over the hotspot. The plate's movement has produced the progressively younger trend of rhyolitic eruptions to the northeast. Between 6 million and 15,000 years ago, numerous basaltic eruptions produced a 4,000-foot-thick sequence of lava flows in the vicinity of Craters of the Moon. Between 15,000 and 2,000 years ago the Craters of the Moon Lava Field formed during eight major eruptive periods. During this time the Craters of the Moon lava field grew to cover 618 square miles. The Wapi and Kings Bowl lava fields formed contemporaneously about 2,200 years ago.

Recent seismic data suggest that the Yellowstone Hotspot left behind a slab of basalt 6 to 10 miles thick. This slab is poised in a mid-crustal position and some of it is thought to contain partial melt. It is believed that this slab represents the slag left in the bottom of the numerous magma chambers spawned by the hotspot. This region is experiencing basin and range type faulting, which is stretching or pulling apart the crust. The Lost River Range north of the town of Arco is good evidence that these forces are still active. In 1983 these forces caused a magnitude 7.3 earthquake, during which Mount Borah rose about 1 foot and the entire Lost River Valley in that vicinity dropped about 8 feet. On the Eastern Snake River Plain, rather than producing mountain ranges, the tensional forces have caused decompression melting, which results in dike emplacement and periodic eruption of molten rock onto the surface. As long as these forces continue to act, more eruptions will eventually occur.

The recurrence interval for eruptive activity in the Craters of the Moon Lava Field averages 2,000 years and it has been more than 2,000 years since the last eruption. The constancy of most recent lava output rates suggests that slightly over one cubic mile of lava will be erupted during the next eruption period. In the past, eruptions in the Craters of the Moon Lava Field have generally shifted to the segment of the Great Rift with the longest repose interval. Therefore, the next eruptive period is expected to begin along the central portion of the Great Rift in the Craters of the Moon Lava Field, but may well propagate to the northern part of the monument in the proximity of the loop road. Initial flows, based on past performance, will probably be relatively non-explosive and produce large-volume pahoehoe flows. Eruptions from potential vents on the northern part of the Great Rift may be comparatively explosive and may produce significant amounts of tephra (airfall material ejected from a volcano), destroy cinder cones by both explosion and collapse, and build new ones.

1.6.2 Geologic Features in Craters of the Moon National Monument

Of the 60 lava flows visible on the surface of the Craters of the Moon Lava Field today, 20 have been dated. The oldest is about 15,000 years old and the youngest about 2,000. Some lava flows were very dense and have a surface of angular blocks—block lava. Others have a rough, jagged, or clinkery surface—áa lava. Still others have a smooth, ropy, or billowy surface—pahoehoe lava. Three special kinds of pahoehoe may be observed in the Craters of the Moon Lava Field: (1) slab pahoehoe, also informally known as semihoe, is made up of jumbled plates or slabs of broken pahoehoe crust; (2) shelly pahoehoe, which forms from gas-charged lava, contains small open tubes, blisters, and thin crusts; and (3) spiny pahoehoe, which is very thick and pasty, contains elongated gas bubbles on the surface that form spines. The spiny variety is pahoehoe that solidified while in a transition phase to áa.

Four kinds of volcanic bombs are found at Craters of the Moon, all of which began as a volume of molten rock that is ejected into the air. If the lava gets twisted during its flight it is called a spindle bomb and typically measures from a few inches to several feet in length. If it is very tiny and twisted, it is called a ribbon bomb. When the volume of lava forms a crust that is cracked by expanding gases as it flies through the air, it is called a breadcrust bomb, which exhibits a surface texture that resembles bread rising in the oven. If the lava mass does not completely solidify during flight, so that it flattens and spreads on landing, it is called a cow-pie bomb. Some cow-pie bombs are over 10 feet long.

Lava tubes are hollow spaces beneath the surface of solidified lava flows. They are formed by the withdrawal of molten lava after the formation of the surface crusts. Indian Tunnel, in the northern area of the park, has a 40-foot high ceiling and is 800 feet long. Bear Trap Cave, which lies between the Craters of the Moon and the Kings Bowl Lava Fields, is about 15 miles long, but is not continuously passable.

Most of the Craters of the Moon lava flows are composed of pahoehoe and were fed through tubes and tube systems, although there are some sheet flows. At Craters of the Moon, structures representing both inflation and deflation of the lava surface can be seen along with hot and cold collapses of the roofs of lava tubes. Inside lava tubes one can see lava stalactites, remelt features, and lava curbs. In other places lava flows formed ponds, built levees, and produced lava cascades. Some lava flows produced small mounds (tumuli) or elongated ridges (pressure ridges) on their crusts. In some places squeeze-ups formed when pressure was sufficient to force molten lava up through tension fractures in the top of pressure ridges or cracks in the solidified crust of lava ponds. Pressure plateaus were produced by the sill-like injection of new lava beneath the crust of an earlier flow that had not completely solidified.

When magma emerges at the surface along a segment of a rift, it often begins by producing a curtain of fire and a line of low eruptions. As portions of the segment become clogged, the fountains jet higher. If magma emerges at the surface highly charged with gas it sprays high in the air; the fire fountains that produced many of the Craters of the Moon cinder cones were probably over 1,000 feet high. Big Cinder Butte, the tallest cinder cone at Craters of the Moon, is over 700 feet high. The highly gas-charged molten rock cools and solidifies during flight and rains down to form cinder cones. If you look closely at cinders you will see that they are laced with gas holes and resemble a sponge.

Some vents along the rift ejected very fluid particles (spatter) that accumulated to form steep-sided spatter cones. Along eruptive fissures where a whole segment erupted, spatter accumulated to produce low ridges called spatter ramparts. Hornitos, also known as rootless vents, are similar in appearance to spatter cones. Hornitos form from spatter ejected from holes in the crust of a lava tube instead of directly from a feeding fissure. Craters of the Moon also has collapse features known as sinks or pit craters. During some eruptions, pieces of crater walls were carried off like icebergs by lava flows. These wall chunks are known as rafted blocks; the monoliths on the North Crater Flow Trail are excellent examples of these volcanic formations.

2.0 Results of Geoindicators Scoping Meeting

The scoping meeting for Craters of the Moon National Monument was conducted on August 31 and September 1, 2000, prior to the Presidential Proclamation that expanded the monument approximately 13½ times it's original size (see Map 1). The newly acquired areas encompass primarily BLM lands to the south and provide additional aquatic resources such as numerous playas and intermittent streams. The BLM administered portion of the monument has both cattle and sheep grazing, as well as some manipulation of the land in support of these activities. Their impact on soils, vegetation, water bodies and other park resources has not been factored into this report.

A decision was made during the scoping session to confine the discussions to the existing park boundary (original park boundary) at that time of the meeting. The contents of this report do not specifically address geologic processes influenced by human activities on the 661,287 acres of newly acquired land. However, most of the scoping meeting's general discussions and recommendations are applicable.

2.1 Geologic Processes Present at Craters of the Moon

The group identified seventeen geologic processes occurring in the park. Eight were considered to be of significant importance to the park ecosystem and of those, three of the processes (stream channel morphology, streamflow and soil/sediment erosion) were identified as having been significantly influenced by human activities.

Eight geologic processes were identified as high management concern and include: frost wedging, ground and surface water quality, streamflow, wetland, volcanic unrest, cave temperature/humidity.

Table 1 lists the geoindicators (a proxy for geologic processes) that are applicable to Craters of the Moon National Monument and indicates the relative ecological importance, human influence, and management significance of each one as rated by the scoping meeting work group. These geoindicators were adapted from Berger (1995). Description of these processes and their importance at Craters of the Moon National Monument are listed below.

Table 1. GPRA IB4 Data Set for Craters of the Moon National Monument - Ecological importance, degree of human influence, and management significance of selected geoindicators at Craters of the Moon National Monument

Geoindicator	Ecological Importance	Human Influence	Management Significance
Alpine and Polar			
Geological controls on perched water systems	**H**	L	M
Frozen ground activity (frost wedging)	L	L	**H**
Arid and Semi-Arid			
Desert microbiotic crusts and pavements	**H**	L	M
Eolian processes	**H**	M	M
Groundwater			
Groundwater chemistry in the unsaturated zone	L	L	M
Groundwater level	**H**	M	M
Groundwater quality	L	L	**H**
Surface Water			
Surface water quality	M	M	**H**
Stream channel morphology	M	**H**	M
Streamflow	**H**	**H**	**H**
Wetlands extent, structure and hydrology	**H**	M	**H**
Geologic Hazards			
Volcanic unrest	**H**	L	**H**
Seismicity	L	L	L
Other (multiple environment)			
Soil and sediment erosion (water)	L	**H**	M
Soil compaction	L	M	M
Cave temperature and humidity regime	**H**	L	**H**
Hillslope processes	M	M	L

H – HIGHLY influenced by, or with important utility
M – MODERATELY influenced by, or has some utility
L – LOW or no substantial influence on, or utility

2.2 Description of Geoindicators for Craters of the Moon

2.2.1 Alpine and Polar Geoindicators:

Geologic Controls on Perched Water Systems

Subsurface ice lenses in caves and buried underground have significant influence on surface water sources at the park. Many ice lenses in caves persist into the early summer, long after all surface snow has melted, and some persist year round. These may be important sources of water for wildlife. Groundwater is generally 1,000 feet below the surface out in the lavas, but water holes perched over ice lenses are present in a number of places. Surface water is scarce in the park and thus the presence of water holes and wetlands and the geologic processes that create and maintain them are critical to plant and animal species. Despite their ecological importance, little information is known about these ice lenses.

Frozen Ground Activity (Frost Wedging)

Frost wedging is the prying apart of materials, commonly rock, by the expansion of water contained in cracks, pores, or along bedding planes upon freezing. The prying force is not necessarily confined to the 9% volume expansion that accompanies the freezing of water, but includes the directional growth of ice crystals and the extension of cracks by hydrofacturing. Where water can migrate and ice crystals can grow, the tensile strength of rock is exceeded, and it splits. The result is that large accumulations of angular rock debris are characteristic of environments with active freeze thaw cycles.

At the park, frost wedging breaks down the surfaces of lava flows and cave roofs. Freeze thaw is concentrated at skylights or cave entrances and is a perennial safety concern for producing loose rock and or rock fall. Frost wedging can also cause rock fall or ceiling collapse within lava tubes though probably less frequently than near entrances.

2.2.2 Arid and Semi-Arid Geoindicators:

Desert Microbiotic Crusts and Pavements

Thin crusts up to several centimeters thick can form in and on top of the soil in arid and semi-arid regions. Microbiotic crusts (also known as cryptogamic soil) are composed of mosses, algae, diatoms, bacteria, fungus, lichens, and other organisms that are interlaced with soil/sediment particles forming a mat. Microbiotic crusts and desert pavements play a critical role in desert environments by armoring the surface and protecting the underlying fine material from wind and water erosion. Microbiotic crusts also contribute to soil fertility through nitrogen fixation, organic carbon contributions, and accumulation of soil fines.

Microbiotic crusts are found in the monument. However, little information is available on this park resource.

Eolian Processes
The action of wind on exposed sediments and friable rock formations causes erosion and the entrainment of sediment and soil particles increases abrasion. Many of the limber pines in the monument are flagged, even at this low elevation because of abrasion of terminal buds by both wind blown sediment in the summer and snow in the winter. Flagged is a term usually used to refer to trees with branches dominantly on one side and typically found near tree line. This process of abrading the terminal buds and preventing growth on the windward side is occurring in Craters of the Moon at a much lower elevation that tree line. What is not known is how much of the effect can be attributed to abrasion by snow and ice in the winter and how much is due to sand blasting in the summer.

Ripples can be observed to migrate on the cinder cones during high winds and particularly in areas that have been burned by fires on older flows, small dunes can be observed to form and migrate. Roots have been exposed by wind erosion in various places in the park. Waysides, which have now been removed from the top of Inferno Cone, seemed to contribute to wind erosion there. Older lava flow areas where thick deposits of loess have accumulated are particularly sensitive to fire, which results in rapid change caused by eolian processes. The removal of vegetation by fire can result in dust storms and the transport of huge volumes of material into unburned areas. Without vegetative cover, dune formation/destruction/migration is activated, surface ripples become common, and numerous small deflation basins can form. Lag deposits may result from the deflation (removal) of fine material from the surface leaving a residue of coarse particles, notable on many of the cinder cones. The potential for deflation is generally increased by vegetation die-back due to animal activity, such as grazing, and by human actions such as recreation and construction projects. At the park the vegetation distribution on cinder cones appears erratic and seems to be primarily driven by deposition of wind blown loess, although the physical and chemical properties of different lava flows may also control vegetation distribution.

2.2.3 Groundwater Geoindicators:

Groundwater Chemistry in the Unsaturated Zone
The unsaturated zone may store and transmit pollutants, the release of which may have an adverse impact on groundwater quality. Little is known about the groundwater chemistry in the unsaturated zone at Craters of the Moon. A spill kit with absorbent material is maintained at the visitor center for such things as a leaking radiator or oil pan in order to try and prevent such materials entering the unsaturated zone or the water table.

Groundwater Level
Groundwater is a major source of water in many regions and in arid regions it is generally the only source of water. At the park, determination of groundwater level is important because it may prove to be a better water source for park operations than the current surface water system. A new test well was drilled in October 2000, and if

brought on line may provide the majority of the water needs for the visitor center complex. Groundwater levels also control the existence of wetlands associated with seeps and springs in the Pioneer foothills.

Groundwater Quality

Groundwater is important for human and animal consumption, and changes in quality can have serious consequences. It is also important for the support of habitat and for maintaining the quality of base flow to streams. At the Park, groundwater quality is important because it may prove to be a better water source for park operations than the current surface water system. Groundwater quality also influences wetlands within the park. The foothills of the Pioneer Mountains contain mineralization and there are a number of dog holes or test pits within the park as well as the old Martin Mine, which has been reclaimed. There are therefore natural sources that can contribute to acidic and heavy metal contamination. In winter, road salt and all year vehicular leakage may contribute to groundwater pollution along the highway corridor. It is not known if there were any disposals or leaks of toxic materials associated with the Craters of the Moon Inn, cabins, and gas station (removed in the 1950's) or from past waste disposal practices. It is unknown what role human waste plays as a contaminant in remote areas. Some of the high visitation lava tubes smell of urine in the summer.

2.2.4 Surface Water Geoindicators:

Surface Water Quality

Clean water is essential to life. Water quality data are essential for the implementation of responsible water quality management, for characterizing and remediating contamination, and for the protection of the health of humans, animals, and plant life. The park currently supplies its water needs from one of two perennial streams within the monument, though it has several wells. Surface water quality in this stream is important because it is currently the primary source of drinking water. Surface water is scarce in this arid environment (average total precipitation for the three months of June, July, and August is 3.1 inches) and thus surface water quality is critical to wildlife. The only source of contamination within the Park's boundary, the Martin Mine, has been reclaimed.

Stream Channel Morphology

Streams are dynamic and can produce rapid changes in landforms, such as channel shape, bedforms, bars, terraces and stream banks. Channel dimensions (width, depth, meander wavelength, and gradient), channel pattern (braided, meandering, straight) and sinuosity are significantly affected by changes in flow rate and sediment discharge, and by the ratio of suspended sediment to bed load.

At the park, stream channel morphology has been altered by human activity. The two perennial streams in the north end of the monument are both first order streams. On Little Cottonwood Creek, the morphology has been altered in the vicinity of the spring boxes in the headwaters area and in proximity to the now reclaimed Martin

Mine. Both Leach Creek and Little Cottonwood Creek have been altered in their lower reaches in what is called the sink area, where they disappear.

Streamflow

Streamflow directly reflects climatic variation. Changes in streams and streamflow are indicators of changes in basin dynamics and land use. Natural variations in streamflow predominate, but can be strongly modified by human actions. Some seeps and springs found in the foothills of the Pioneer Mountains within the park give rise to small wetlands.

Springs also give rise to Little Cottonwood Creek and Leach Creek and their attendant riparian habitats. Over the years the park has acquired the land so that the drainage basins for Little Cottonwood Creek and Leach Creek lie within the park boundaries. This will prevent outside impacts, such as new mining activities from influencing in-stream flow and water quality.

Park operations are the only non-natural factor influencing volume of flow. Current use of Little Cottonwood Creek for administrative use, i.e. the potable water supply for the park, has dramatically reduced in-stream flow. During the summer high visitation season the park use averages about 20 gallons per minute. The park may be able to utilize a new well in the future, which will allow natural in-stream flows to be returned and the riparian habit to readjust to the restoration of natural flow conditions. Stream systems play a key role in the regulation and maintenance of biodiversity. Because of the very limited area of riparian habitat within the park, it is important that the park move in the direction of restoring as much in-stream flow as possible, while meeting its administrative needs.

Wetlands extent, structure and hydrology

Wetlands are areas of high biological productivity and diversity. They provide important sites for wildlife habitat. Wetlands can mediate large and small-scale environmental processes by altering downstream catchments and serving as flood buffers. Wetlands can also affect local hydrology by acting as a filter, sequestering and storing heavy metals and other pollutants. Wetlands are of very limited aerial extent within the park making their health of great concern. They are primarily found in the foothills of the Pioneer Mountains and are associated with seeps, springs, and riparian areas. These areas in the north end are closed to visitor use, which safeguards them from visitor impact. As mentioned in prior sections, stream morphology was altered in the past for Leach Creek and Little Cottonwood Creek and flow is currently altered by administrative use of water from Little Cottonwood Creek.

2.2.5 Geologic Hazards Geoindicators:

Volcanic Unrest

Volcanic eruptions are almost always preceded and accompanied by volcanic unrest indicated by variations in the geophysical and geochemical state of the volcanic system. Such geoindicators commonly include changes in seismicity, ground deformation, nature and emission rate of volcanic gases, fumarole and/or ground temperature, and gravity and magnetic fields. Volcanic unrest can also be expressed by changes in temperature, composition, and the level of crater lakes, and by anomalous melting or volume changes of glaciers and snow fields on volcanoes. When combined with geological mapping and dating studies to reconstruct comprehensive eruptive histories, these geoindicators can help to reduce eruption-related hazards to life and property. However, not all volcanic unrest culminates in eruptions: in many cases the unrest results in a failed eruption in which the rising magma does not breach the surface and erupt.

Much of the park is underlain by the Craters of the Moon lava field, which is a composite of more than sixty lava flows grouped into eruptive periods. Eight eruptive periods began about 15,000 years ago and ended about 2,000 years ago. Each of the eruptive periods were about 1,000 years or less in duration and were separated by intervals of quiescence lasting from a few hundred years to more than two thousand years. The chance of future volcanic eruptions at the park is very high.

Seismicity

Crustal movements along strike-slip, normal and thrust faults cause shallow-focus earthquakes (those with sources within a few tens of kilometers of the Earth's surface), though they can also be induced anthropogenically. They can result in marked temporary or permanent changes in the landscape, depending on the magnitude of the earthquake, the location of the epicenter, and local soil and rock conditions. Surface effects include uplift or subsidence, surface faulting, landslides and debris flows, liquefaction, ground shaking, and tsunamis. Deep-focus earthquakes (below about 70 km), unless of the highest magnitude, are unlikely to have serious surface manifestations. To avoid, reduce or warn of environmental impacts, it is necessary to know the size, location, and frequency of seismic events. These parameters can identify active faults and the sense of motion along them. Also of great importance is the spatial pattern of seismicity, including the presence of seismic gaps, and the relationship to known faults and active volcanoes.

The park lies in a seismically active area, however, the plain is aseismic in general. The Great Rift, a more than 50-mile long NW-SE trending volcanic rift zone, along which the Craters of the Moon, Kings Bowl, and Wapi Lava Fields lie, has the same basic orientation as the Basin and Range Extension. It is believed that the crustal extension is being accommodated on the Snake River Plain by dike emplacement. Dikes have periodically reached the surface producing volcanic eruptions. Numerous non-eruptive fissures and open-crack sets exist within the park. There is a prominent fault scarp across from the visitor center that may be related to subsidence back into the magma chamber after the North Crater eruptions. There are also prominent faults on North Crater and Broken Top cones. There is one seismograph station in the park located near Grassy Cone. This station may serve as an early warning system by recording such things as harmonic tremor.

Current park facilities survived the Borah Peak 7.3 event; however any new facilities should be built to meet appropriate seismic construction codes.

2.2.6 Other Geoindicators:

Soil and Sediment Erosion (Water)
Soil erosion is an essential factor in assessing ecosystem health and function. Removal of soil occurs primarily through fluvial processes (erosion by water) such as sheet, rill, and gully erosion. When runoff occurs, less water enters the ground, thus reducing the moisture available to vegetation. Soil erosion also reduces the levels of the basic plant nutrients and decreases the diversity and abundance of soil organisms. Stream sediment can degrade water supplies and provide a transporting medium for a wide range of chemical pollutants. Increased turbidity due to fine sediment loads may adversely affect aquatic organisms such as benthic algae, corals and fish. Erosion is a fundamental and complex natural process that is strongly modified (generally increased) by human activities such as land clearance, agriculture, forestry, construction, surface mining and urbanization.

High infiltration rates of soils and parent material at the park make fluvial erosion much less significant that eolian erosion in most areas. Concentrated runoff from parking lots and roadways is causing some gullying. Occasionally, after heavy or prolonged rain there is a small amount of rill formation on some of the hiking trails. These rills usually disappear after a small amount of foot traffic.

Soil Compaction
As one of Earth's most vital ecosystems, soil is essential for the continued existence of life on the planet. As sources, stores, and transformers of plant nutrients, soils have a major influence on terrestrial ecosystems. Soils buffer and filter pollutants, they store moisture and nutrients, and they are important sources and sinks for carbon dioxide, methane and nitrous oxides. Soil structure may be altered so that infiltration capacity and porosity are decreased, and bulk density and resistance to root penetration are increased. Such soils have impeded drainage and are quickly saturated, the resultant runoff can cause accelerated erosion and transport of pollutants.

The park has localized areas of soil compaction due to human activities and wildlife pathways. There are numerous game trails or animal highways primarily created by mule deer. Human trails and social trails also cause compaction. Though grooming for cross-country skiing is now limited to the roadways, in the past a trail was groomed on the side of Inferno Cone for one season. This has resulted in a compaction scar, which is visible on the side of the cone nearly 10 years later.

Cave Temperature and Humidity Regime
Temperature and humidity changes are moderated in caves compared to the changes that occur on the surface. Barring large-scale disasters like earthquakes, the nature of any particular cave environment will remain constant on a human time scale.

However, the cave environment can be dramatically altered by human activities. Small changes in temperature and humidity can have substantial effects on cave-adapted organisms. The most serious human alteration to airflow in any of the lava tubes in the park was in Arco Tunnel, where a gated-culvert and rockwork significantly reduced the cross-sectional area of the tube. A new bat friendly gate was installed in 1999 and the old culvert and rockwork were removed in 2000.

Hillslope Processes

Hillslope processes include slope failures due to mass wasting (rock falls, landslides, debris flows, slumps, soil creep) as opposed to fluvial erosion. There are many ways in which slopes may fail, depending on the angle of slope, the water content, the type of earth material involved and local environmental factors such as ground temperature. Mass wasting may take place suddenly and catastrophically, resulting in debris and snow avalanches, lahars, rock falls, slides and flows. Slower movements result in slides (debris, rock blocks), topples, slumps (rock, earth), complex landslides and creep. There are innumerable small to medium-size slope failures that cumulatively impose costs to ecosystems as great or greater than the large infrequent catastrophic landslides that draw so much attention. Landslides can alter habitats, for example by blocking streams, increasing sediment delivery to streams and denuding slopes.

In the park, some cinder cones because of being armored with spatter or because of agglutination have slopes steeper than the normal angle of repose for cinders. There is prominent evidence of slumping on North Crater and on Broken Top. A number of cones have evidence of rock falls and landslides. Some of slopes in the foothills of the Pioneer Mountains are also susceptible to rock falls, landslides, and slumps. All slopes in the park are susceptible to soil creep. Avalanches occasionally occur on slopes over 25 degrees, both point releases and slab. Trail projects (maintenance or new construction) should take potential rock falls, slumps, and landslides into account.

2.3 Geologic Processes Highly Influenced By Human Activities

Geologic processes can be influenced by human activities by extraction of material, alteration of processes for park operations or by visitor use impacts. Additional impacts to park resources can be caused by human activities outside park boundaries. An understanding of how human activities are impacting geologic processes will assist managers in protecting natural resources. At Craters of the Moon, diversions of water from Little Cottonwood Creek have had significant impacts on streamflow, channel morphology and the development of the visitor center complex has altered runoff patterns and increased erosion.

2.3.1 Streamflow and Stream Channel Morphology

Only two perennial streams, Leach and Little Cottonwood Creeks, are present in the park. These streams drain the Pioneer Mountains in the north end of the park. Streamflow in Little Cottonwood Creek began being diverted out of the stream in the 1930's for park operations. Water demand was low until the late 1950's when the visitor center complex was built. Streamflow above or below the diversions, or the amount used by the park have not been measured, but it is estimated that peak consumption occurred in the 1960's when over 50% of the streamflow was diverted out of the channel. This use has decreased to approximately 30% of the streamflow today due to the reduction in the area irrigated for lawns. The water system is inefficient and more water is diverted from the stream at the intake than the park actually uses.

The peak water demand corresponds with the lowest streamflows during the summer months. The water diversion may increase the stress to plants and animals dependent on Little Cottonwood Creek as a source of water during the driest periods of the year. However, since the maximum diversion occurs during the lowest streamflow periods, the diversion is not thought to significantly alter stream channel morphology.

The park drilled a test well in the fall of 2000 and is evaluating the feasibility of using groundwater from this well as the park's water supply instead of the current surface water supply.

There is evidence that the lower portion of Little Cottonwood Creek was historically diverted out of its natural channel. The creek makes a 90° bend; there is a line of dead cottonwoods and a depression that indicate where the channel used to be. The channel morphology of Leach Creek has also been altered. There are old impoundments or control structures in the upper portions of the creek. A dry channel in the lower portion indicates that the creek was historically diverted out of its natural channel.

Both creeks continue to be diverted out of their original channels. The diversions have had significant effects on the riparian vegetation and channel morphology below the diversions. It is possible that these diversions may be impacting groundwater recharge.

2.3.2 Soil and Sediment Erosion (Water)

Human influences on soil and sediment erosion are due to the alteration of natural hydrologic patterns by developments. Parking lots and roadways, particularly in the vicinity of the visitor center complex, impede infiltration, increase runoff, and concentrate water. This runoff has caused gullies where the water leaves the pavement.

2.3.3 Soil Compaction

Another process that was discussed and rated as being moderately influenced by human activities was soil compaction, primarily related to social trails created by visitors walking off trails. Though spatially this affects a very limited area of the park, and has a very minor impact on the ecosystems, hiking off trail does impact the visual landscape and aesthetics of some of the high visitation areas. The expansion of the width of the trail up Inferno Cone is a very visible example. Social trails remain visible for many years at the park. However, the very porous nature of the cinder cones allows infiltration to remain high despite the soil compaction. Therefore, erosion is not expected to increase as a result of social trails.

The park has taken steps to limit soil compaction from hiking off trail and other activities. Resource protection messages are given during ranger-led walks and talks and all visitors passing through the entrance station receive a handout on “Staying on the Trails”. Resource management has experimented with using lodgepole pine poles to delineate the edges of trails and cairns with posts and reflective tape to mark trails across rocky areas. Grooming for cross-country skiing is now restricted to the roadway. Curbs have been placed along almost all of the loop drive and spur roads to discourage vehicles from leaving the pavement. Signs along the roadway inform visitors that driving off road is prohibited. Bicycles are not permitted on any of the hiking trails.

2.4 Geologic Processes with High Management Significance

Geologic processes can have high management significance due to safety concerns, administrative use of resources and protection of fragile resources from deleterious human activities. It is important for managers to be aware of what geologic processes are active in a park and how to adapt management to them. This knowledge can greatly assist managers in making decisions to protect human safety and natural resources.

At Craters of the Moon National Monument, frost wedging resulting in loose rock, rock fall or potential collapse in lava tubes, and volcanic unrest can be hazardous to humans and need to be monitored in order to protect visitors and park staff. Surface and groundwater quality are important to managers because this water is used for park operations. Likewise, streamflow and wetland health are concerns to managers because the park’s withdrawal of water may be damaging these critical resources. Cave temperature and humidity regimes are also significant to managers because cave ecosystems are very sensitive to human disturbance.

2.4.1 Frozen Ground Activity (Frost Wedging)

The breakdown of cave roofs and surfaces of lava flows is of high management significance because of the safety concerns. Stability of cave roofs, particularly those with high visitation, needs to be monitored so that instability can be detected and appropriate safety measures taken. These safety measures may include closing the cave or stabilizing the roof.

2.4.2 Groundwater Quality

The park is considering shifting its water supply for drinking water and other park operations from a surface water to a groundwater source. If this occurs, monitoring groundwater quality will be important to protect public health.

Dept. of Energy (DOE) Idaho National Engineering and Environmental Lab has an active groundwater quality monitoring program to determine the water quality beneath the DOE Site and what is possibly leaving their boundaries, which would eventually migrate beneath the monument.

2.4.3 Surface Water Quality
The park currently gets all its water for drinking and other park operations from surface water. The quality of this water needs to be monitored to protect the health and safety of park staff and visitors. The natural water quality will also determine the degree of treatment and maintenance of pipelines and treatment systems needed to make it fit for human consumption. Management is also concerned about the effects of surface water quality on the ecosystem because water is so scarce in the park.

2.4.4 Streamflow
The park currently gets all its water for drinking and other park operations from surface water. Information on streamflow is needed to determine the capacity of the stream to provide water to park operations and the ecological effects of diverting this water out of the channel.

2.4.5 Wetlands Extent, Structure and Hydrology
Surface water is scarce in the park, so any wetlands are thought to provide critical water and habitat for wildlife. Management is concerned about the possible ecological effects of diverting surface water for park operations, which may contribute to dewatering of the natural wetland downstream of the diversion.

2.4.6 Volcanic Unrest
Should volcanic activity resume, there is expected to be increased interest in and visitation to the park that will create new safety concerns. Management is concerned about how to handle this potential increased interest and visitation and also provide for visitor safety should volcanic activity recur.

2.4.7 Cave Temperature and Humidity
Cave formations and animal species are very sensitive to changes in the cave environment, particularly changes in temperature and humidity. Caves are also a primary visitor attraction. Management is concerned that visitor use and human caused alterations to the caves (such as altering an opening to make human passage easier) will damage cave resources and alter the temperature and humidity regime. Some caves are currently closed seasonally to minimize disturbance to wildlife. Arco tunnel is closed from Sept. 15th to May 15th to protect the bats that use it as hibernacula. There are also other closures, such as the North End caves, to protect bats.

3.0 Recommendations

3.1 Recommendations to Minimize Known Human Influences on Geologic Processes

- Continue to evaluate the possibility of using groundwater for park operations instead of the current diversion of surface water from Little Cottonwood Creek.
- Monitor discharge of Little Cottonwood Creek at multiple points and quantify the amount of water diverted out of the channel and the amount actually used by the park. Determine the baseline park water needs during critical summer low flows and high visitor use.
- Improve the efficiency of the water diversion system and minimize leaks so that only the amount of water used by the park is diverted from the creek.
- Conserve water to the greatest extent possible. Post signs at water faucets (campground and visitor center) educating visitors on the scarcity of water in this environment and encouraging water conservation.
- Analyze historic air photos to determine the pre-disturbance location of the lower portion of Little Cottonwood Creek and Leach Creek and the extent of human manipulation of the channel.
- Consider restoring the lower portion of Little Cottonwood Creek to its pre-disturbance channel.
- Evaluate runoff from parking lots and roadways to ensure that water is being discharged off these paved areas at locations and in ways that minimize erosion. This can include dispersing the flow, discharging the water in areas that are less prone to erosion, or rock armoring the locations where the water leaves the pavement.

3.2 Recommendations to Increase Knowledge of Resources and Processes

3.2.1 Inventory Needs

- Inventory surface water holes/ponds and wetlands out in the lavas. Compare to locations on old topographic maps to determine if some have disappeared or if new ones have formed. The locations of these water holes/ponds could also be compared to the age of the lava flows on which they sit.
- Inventory wetland location and extent and associated wetland vegetation.
- Inventory location, type, and composition of speleothems, such as sulfate crystals, in caves and monitor them over time to determine rates of formation and dissolution. Inventory type, size, quality, and location of remelt structures with lava tubes.
- Explore for and inventory location of tree molds (trace fossils).
- Inventory and assemble database of types, quality, and location of various volcanic features.
- Inventory the location and extent of microbiotic crusts in the monument. Determine its importance to the park ecosystem and if microbiotic crusts are influenced by human activity.

3.2.2 Monitoring Needs

- Monitor quality of surface water used for drinking and other park operations.
- Monitor stability of cave roofs in order to protect visitor safety.
- Monitor temperature and humidity in selected caves.
- Create and monitor some additional geologic transects or photo interpretation points of critical geologic features.

3.2.3 Research Possibilities

The following research topics have been identified and are currently unfunded:

- Study ice lenses and geologic controls of perched water systems. Determine the distribution, size, and persistence of ice lenses and the geologic processes that create and maintain them. Evaluate the relationship of ice lenses to the presence of water holes and wetlands in the park, and study the ecological importance of ice lenses to supporting and maintaining the associated plant and animal ecosystems.
- Compare development of microbiotic crusts and desert pavements to the age of the lava flows on which they are formed to determine the length of time they take to form and the process through which they evolve.
- Study wind blown dust and snow/ice as well as the deposition of loess to determine how these control vegetation distribution. Also evaluate the characteristics and chemical composition of the lava flows to determine what effect that has on vegetation distribution. Also consider the effects of fire on vegetation distribution.
- Study wind blown dust and snow/ice to determine the degree each affects the flagging of branches on limber pines.
- Measure water quality in Little Cottonwood Creek above and below the mine tailings during various flow events to determine the effect of the tailings on water quality.
- Conduct a geochemical analysis of volcanic glass of various flows to determine the cause of the different colors and if the prevalent blue color is caused for the same reason on different flows of different ages and composition.
- Study density of rafted blocks and the lava flows transporting them and determine the fluid mechanics involved.
- Map and sample complex areas, such as the Broken Top area, in detail (1:1000 scale) to work out the geology of the areas.

3.3 Other Recommendations Utilize Geologic Findings

3.3.1 NPS Planning Process

We urge the Park to take advantage of the information provided in this report to make management decisions and incorporate it into appropriate planning documents, such as the General Management Plan, the Visitor Enjoyment Resource Protection Plan and the Resource Management Plan and Statements.

3.3.2 NPS Vital Signs Monitoring Program

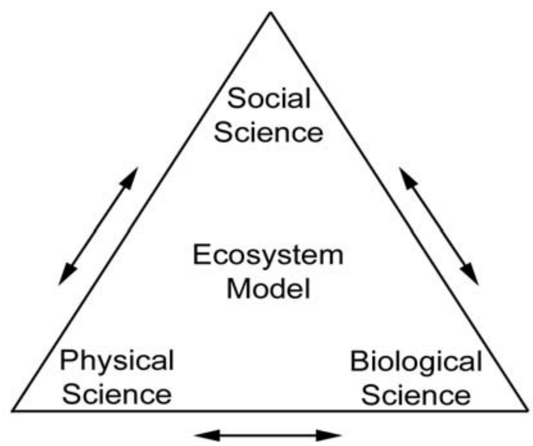
We urge the Park to take advantage of the information provided in this report when identifying indicators for vital signs monitoring. The inventory needs identified above should be considered essential for establishing baseline conditions in the park. The monitoring and research needs identified above should be considered when selecting what to include in the park's long-term monitoring program.

4.1 Appendix 1

Geologic Processes - Role and Importance in Ecosystems

Ecology is a branch of biology that seeks to understand the interactions among organisms and between organisms and their physical world. Despite the importance of the physical environment to ecology, the geosciences traditionally have not been integrated into land management or ecosystem planning. This is, in part, because traditional approaches to land management perceived the landscape as a web of biological processes playing out on an inert geological stage as opposed to perceiving the landscape as a collection of processes – biological, geological, and social – that are inter-related and inter-dependent. (See Figure 1).

Figure 1. The triangular diagram illustrates conceptually how the basic sciences of ecosystem study contribute to our understanding and development of an ecosystem model.



Through the last two decades, the focus of land management has slowly been shifting from the former approach to the latter. This changing philosophy brings a need to devote increased attention to the geosciences, and especially to the interactions between the geologic and biological systems.

Geology is a major determinant of the topography, the water and soil chemistry, the fertility of soils, the stability of hillsides, and the flow styles of surface and groundwaters. These factors, in turn, determine where and when biological processes occur such as the timing of species reproduction and the distribution of habitats. Likewise, biological processes affect geological processes. For instance, biological activity contributes to soil formation and soil fertility, controls hillside erosion, traps blowing sand to form sand dunes, stabilizes drainages, and attenuates floods.

A challenge in appreciating the relevance of geology is that geologists often work with very long relative time scales; whereas, life-science specialists deal with much shorter time scales (Hughes and others, 1999). However, geologic processes occur over a variety of temporal and spatial scales. At one end of the temporal spectrum lie the processes that occur over millions of years such as the rising of a mountain range or the widening of a rift. At the other end lie the processes that occur virtually instantaneously (and often catastrophically) such as floods, landslides, and earthquakes. Between these extremes are processes that are not easily pinpointed in time but are rapid enough that we can easily observe changes in geologic features as they occur. Often, they occur continuously or in repetitive cycles. Examples of these are shoreline movement, river transport of sediment, soil formation, and cave development.

Geologic processes are as diverse spatially as they are temporally. The absorption of chemical elements to sediment particles may be the key process in determining groundwater chemistries. This process occurs at the microscopic level. In contrast, the geothermal activity at Yellowstone or Lassen Volcanic Park is related to the movement of tectonic plates at a global scale.

Geological processes that most directly impact biological processes include the following: stream and groundwater flow and their variations, erosion and deposition, weathering and mass wasting (landslides, rockfalls), earthquakes, and volcanic phenomena (eruptions, hot springs). These processes collectively operate on a variety of time scales, and the time scale of each process by itself may vary over time. It is possible for all of these processes to be operating at once in a single park. For example, an eruption in Hawaii Volcano National Park is usually accompanied by earthquakes, though minor, and can include landslides, stream diversion by lava flows, and buildup of topography when the lava flows freeze. These processes destroy some habitats while creating others, and introduce new substrates for early successional stages, thus maintaining habitats for early successional species. In other words, even on human time scales, the geological substrate for ecosystems is as dynamic and constantly changing as are the ecosystems themselves. In fact, one cannot understand ecosystem dynamics without also understanding the dynamics of their substrate. This type of human-scale geologic process also can impact the visitors to the parks by presenting potential hazards. (Parrish and Turner, 2000)

Even what is viewed as a static geologic resource contributes to ecosystem mosaics and biodiversity. For example, in Grand Canyon National Park, the nesting sites of the spotted owl are restricted to ledges formed in a specific rock layer in the park, the Hermit Shale. Thus, management of the nesting sites of this threatened species requires knowledge of the geologic substrate. Understanding why this rock layer is so important to the owls indicates the need for integrated biogeological research. An example of floral dependence on geology is the Winkler's cactus, which grows only on the white, powdery soil and pebbles eroded from part of the Morrison Formation in Canyonlands National Park. In this case, not only is the distribution of the rock layer itself important to the plant, but the erosion products themselves are quite fragile, requiring management of both the plant and its delicate habitat. (Parrish and Turner, 2000)

The geologic resources of a park – the soils, the caves, the fossils, the stream network, the springs, the volcanoes, etc. – provide the precise set of physical conditions required to sustain the biological system. Interference with geologic processes and alteration of geologic features inevitably affect habitat conditions. For example, the channelization of the Virgin River in Zion National Park caused the channel to incise, lowering the groundwater table and reducing the habitat of floodplain obligate species (Steen, 1999). In Jean Lafitte National Historic Park and Preserve, externally triggered land subsidence is raising the water level in the park inundating the swamp forest and reducing habitat for forest-dependent species (Sauier, 1994). Alternatively, a manipulation of the biological system can trigger changes in the geologic system that can re-affect the biological system. For example, when beavers are trapped to increase the density of hydrophobic shrub species, the river morphology and sediment transport capacity changes resulting in a redistribution of the types of fish species that dominate.

4.2 Appendix 2

Human Influences on Geologic Processes in and Adjacent to National Park Units

The term "human influences" is the central theme for the second part of this GPRA goal. The term has purposefully been selected in order to explore the full breath of possibilities, both inside the park and external to the park boundaries. Adjacent land use, consumptive activities, administrative practices as well as public visitation can all influence earth surface processes. An effective way to illustrate human influences on the processes is to go through some examples. This is not a comprehensive treatment and these examples do not occur in or adjacent to all parks.

Land Uses (most commonly occurring adjacent to parks)

- Agriculture – intense use can cause loss of soil, erosion, and dust storms. Use of pesticides can affect both surface and groundwater quality.
- Grazing – overgrazing can cause loss of vegetation, soil erosion and create conditions conducive to fires and the spread of non-native species.
- Forestry – intensive logging or clear cutting creates conditions for increased hillslope and fluvial erosion; sediment carried away can cause increased sediment loading in streams that can effect aquatic habitat.
- Water impoundment – This has the potential to affect one segment of a stream or river or the entire watershed. Controlled volume of flow does not duplicate natural events such as floods and drought. It can affect the water temperature, sediment load, and change the stream morphology and habitat that are dependent on such things as flushing flows within a fluvial system.
- Urbanization – This can cause a host of influences, but a few stand outs are; change in drainage patterns, increased runoff and erosion, effects on surface and groundwater quality and quantity, release of toxins into the air and water, and increased humidity in arid regions.
- Dredging, beach mining, river modification, installation of protective structures, removal of back-shore vegetation, and alterations of the near-shore can potentially alter shoreline processes, position and morphology by changing the sediment supply.

Consumptive Uses

- Groundwater withdrawal – In instances where the groundwater resource is depleted to the point where recharge cannot keep pace with withdrawals, the groundwater-dependent ecosystem is effected. Where withdrawal has been intense for a number of decades, the surface has been known to collapse (subside) over huge areas by as much as 10 feet.
- Oil and gas production – this can cause surface subsidence and contamination of water aquifers and cave and karst systems.
- Mining (open pit and underground) – This can reconfigure the landscape over large areas bringing significant and permanent change to the landscape. It can affect the

surface and groundwater by releasing heavy metals or other chemicals into the system, as well as affecting the groundwater level.

- Mineral & Materials Mining – the quarrying of stone, mining of gravel and borrowing of soil, if done in large volume or smaller volume but in critical locations in the ecosystem, impacts geologic process by the shear volume of material removed and pumping to keep the operation dry can lower the water table.

Administrative Uses

- Roads and bridges – Often these have been constructed with little or no consideration for natural processes. Roads can disrupt drainage, cause erosion and create hillslope instability. The abutments for bridges can change the flow and morphology of streams and rivers.
- Parking lots – Large paved areas inhibit infiltration and increase runoff. Water flowing from parking lots can cause erosion and gullying. Runoff pollution effects surface and groundwater.
- Facilities placed over caves – Contaminants from restrooms and other water usage, plus runoff can reach caves and karst systems below causing damage to the fragile subterranean ecosystems.
- Water consumption – In arid and semi-arid environments, water is a scarce and critical resource. Withdrawal of water may have significant impacts on the ecosystems, such as riparian zones.
- Trails – If they are poorly located with respect to soil, rock and vegetation considerations, they have the potential to exacerbate erosion, rock falls and slope instability.
- Armoring streams, rivers and coast – Rock armoring changes the fluvial and shoreline processes thereby affecting the ecosystem by causing such things as increased erosion or deposition down stream of the riprap.
- Planting exotic species – Planting or not controlling non-native species can have a significant effect on erosion and sedimentation processes.

Visitor Use

- Trampling, compaction of soil – Over use by too many people in a small area can compact the soil and can reduce soil productivity and increase erosion.
- Social trails – Depending on the nature of the environment, development of unplanned trails can seriously damage fragile resources (such as in caves, wetlands, microbiotic crust, cinder cones, tundra, etc.)
- Touching fragile features – A number of geologic features have taken years to form through geologic processes, and although seemingly rock-hard, they can be rather fragile. Examples include stalactites and stalagmites in caves. Also included are erosional features, such as arches, bridges, hoodoos, and badlands. Crystals are another example. Visitors touching or climbing on all these features can cause irreparable damage.
- Power boating – Over a period of time, wakes from small and large boats alike can contribute to shoreline erosion. Fuel contamination can affect water quality.

These examples are provided to stimulate the readers thinking, raise awareness and perhaps contemplate additional cases from one's own experience.

4.3 Appendix 3

Geoindicators – A Tool for Assessment

Geoindicators are measures (magnitudes, frequencies, rates, and trends) of geological processes and phenomena occurring at or near the Earth's surface and subject to changes that are significant in understanding environmental change over periods of 100 years or less. They measure both catastrophic events and those that are more gradual, but evident within a human life span. Geoindicators are not geologic processes. However, there is a strong correlation between the two. Geoindicators can be used to monitor and assess changes in fluvial, coastal, desert, mountain and other terrestrial areas. They can also be used through paleoenvironmental research to unravel trends over the past few centuries and longer, thus providing important baselines against which human-induced and natural stresses can be better understood.

Geoindicators describe processes and environmental parameters that are capable of changing without human interference, though human activities can accelerate, slow or divert natural changes (e.g. Goudie 1990, Turner et al. 1990). Humans are certainly an integral part of nature and the environment, but it is essential to recognize that nature and the environment are ever changing at one temporal and spatial scale or another, whether or not people are present. Environmental sustainability must, therefore, be assessed against a potentially moving background. Table 1 is a checklist of 27 geoindicators developed by the International Union of Geologic Sciences through its Commission on Geologic Sciences for Environmental Planning.

Table 1. Geoindicators: natural vs. human influences, and utility for reconstructing past environments.

Geoindicator	Natural Influence	Human Influence	Paleo Reconstruction
Coral chemistry and growth patterns	H	H	H
Desert surface crusts and fissures	H	M	L
Dune formation and reactivation	H	M	M
Dust storm magnitude, duration and frequency	H	M	M
Frozen ground activity	H	M	H
Glacier fluctuations	H	L	H
Groundwater quality	M	H	L
Groundwater chemistry in the unsaturated zone	H	H	H
Groundwater level	M	H	L
Karst activity	H	M	H
Lake levels and salinity	H	H	M
Relative sea level	H	M	H
Sediment sequence and composition	H	H	H
Seismicity	H	M	L
Shoreline position	H	H	H
Slope failure (landslides)	H	H	M
Soil and sediment erosion	H	H	M
Soil quality	M	H	H
Streamflow	H	H	L
Stream channel morphology	H	H	L
Stream sediment storage and load	H	H	M
Subsurface temperature regime	H	M	H
Surface displacement	H	M	M
Surface water quality	H	H	L
Volcanic unrest	H	L	H
Wetlands extent, structure, and hydrology	H	H	H
Wind erosion	H	M	M

H – HIGHLY influenced by, or with important utility for
M – MODERATELY influenced by, or has some utility for
L – LOW or no substantial influence on, or utility for

Note: This table illustrates in a general way the relative roles of natural and human-induced changes, both direct and indirect, in modifying the landscape and its geological systems. However, it excludes from consideration influences that may be brought about by anthropogenically-induced climate change.

4.4 Appendix 4

Description of Geologic Processes

Difference between Geologic Processes and Geoindicators:

Geoindicators are parameters that can be used to assess changes in rates, frequencies, trends, and/or magnitudes in geological processes. See the examples below:

Glaciation is the process by which ice accumulates, flows, and recedes, shaping the land surface over which it moves. Glacier fluctuations, in the geoindicator sense, are changes in ice mass balance and position that are important to track in understanding and forecasting changes to "cryospheric" mountain ecosystems and the river systems that flow from them.

Volcanism is the process whereby magma reaches the surface and erupts to shape the surrounding landscape (and distant landscape through ash and dust falls). Volcanic unrest is the geoindicator that takes into account all the various kinds of changes (geophysical, geochemical and neo-tectonic) that occur prior to an eruption.

Dynamic coastal processes cause changes in sea level, coastal erosion and deposition, wave patterns, and climate. Shoreline position is the geoindicator that helps to assess the cumulative effect of these processes. Relative sea level is a simple measure that relates coastal subsidence and uplift, and changes in the sea-surface elevation that may be due to de-glaciation, thermal expansion (climate warming), or neo-tectonics.

Geologic Processes

The geologic processes operating on the landscape may be divided into two types, exogenetic and endogenetic. Exogenetic processes are those that operate at or near the earth's surface. These processes have a number of agents like wind, water, and ice that cause erosion and deposition and include very basic processes such as mass wasting and physical & chemical weathering. Endogenetic processes are generated within the earth's crust and mantle and include volcanism and tectonism (Toy and Hadley, 1987). These processes shape the configuration of the earth's surface (Easterbrook, 1969).

Fluvial Erosion and Deposition

The precipitation that falls on the earth either runs off the surface, soaks into the ground, or evaporates back into the atmosphere. That portion which runs off the surface of the land eventually collects into rivulets, gullies and streams which continuously erodes the land and deposits material elsewhere. Landscapes sculptured by fluvial erosion and deposition bear characteristic features that differ from those developed by other processes. Oxbows, point bars, alluvial fans, and deltas are but a few examples.

Glacial Erosion and Deposition

Glacial processes also produce unique landforms, such as kames, eskers, drumlins, various kinds of moraines, rouches moutonnees, and many others. Glaciers move more slowly downslope than do streams, but are nevertheless capable of carrying large quantities of material derived by erosion from valley sides and bottoms.

Glaciers produce the classic "U" shaped valleys of glaciated areas, as well as horns, aretes, and cirques. Frozen ground features include such things as pingos, patterned ground, and solifluction ridges.

Groundwater Solution and Deposition
Some of the precipitation that falls from the atmosphere seeps into the ground, where it is stored until it emerges along valley sides and floors, lakes, bays and oceans. While in contact with rock material, groundwater promotes solution and other types of chemical weathering. Transport of weathered and dissolved material leads to development of unique landforms (caves and karst), especially in areas of soluble rocks, such as limestone. Heating of groundwater may result in hot springs, geysers, paint pots, and frying pans, as well as produce siliceous sinter deposits and promote diatom activity.

Mass Wasting
Mass wasting is the downslope movement of soil and rock material under the influence of gravity without the direct aid of other agents, such as water, wind, or ice. Water and ice, however, are frequently involved in mass wasting by reducing the strength of rock and soil and by contributing to plastic and fluid behavior of soils. Mass wasting is capable of transporting large quantities of material from hill slopes to valley floors. Mass wasting can be rapid, for example a rock fall or landslide, or slow as in soil creep.

Lacustrine and Oceanic Processes
Shorelines of oceans, seas and large lakes are modified continuously by the abrasive action of waves beating against the shore and deposition of material by wave and current action. Terraces, spits, bars, turbidity deposits and other features result from these processes.

Eolian Processes
Wind is a less vigorous agent of erosion, transport, and deposition of material than water, but in arid and semiarid regions, or areas having an abundant supply of unconsolidated sand, wind is locally an important agent producing yardang, ventifacts, lag deposits, loess deposits, and dunes. Sand dunes are the main attraction in park units such as Great Sand Dunes National Monument, Colorado, and White Sands National Monument, New Mexico.

Weathering
Mechanical disintegration and chemical decomposition of rocks cause them to be broken down into smaller pieces. In those areas where rocks offer differing resistance to weathering, differential weathering etches out weaker rock zones producing bizarre honeycomb patterns, and coupled with other agents of erosion can cause valleys to develop. In areas where mechanical weathering is dominant, the topography develops angular hill slopes, whereas in areas dominated by chemical weathering, smooth, rounded slopes are developed.

Volcanism

Eruption of lava on the surface produces very distinctive landforms, which if not too old, are easily recognized, such as at Craters of the Moon National Monument, Idaho, Lava Beds National Monument, California, and El Malpais National Monument, New Mexico. These include such features as shield volcanoes, strato or composite volcanoes, cinder cones, various kinds of lava flows, tumuli, hornitos, pressure ridges, spatter cones and ramparts, lahar deposits and many more.

Tectonism

Deformation of the earth's crust caused by tension, shear, and compression may produce initial small scale landforms like fault scarps and sag ponds or produce huge regional scale folding or thrusting that only become exhumed by erosion later. Among common topographic features produced initially by tectonic movement are scarps, horsts, and grabens. Fault gouge is more easily eroded than unfractured rock, which can hasten the process of erosion. Relief of pressure from faulting can result in decompression melting, dike emplacement, and even volcanic eruption. Tectonism is a process that frequently is working in concert with other processes.

5.0 References

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